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Embedded Energy Storage Systems in the Power Grid for Renewable Energy Sources Integration

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1. Introduction

The increasing integration of renewable energy sources in the power system allows a reduction of the fossil fuels consumption and on their consequent environmental impacts, such as the climate change and air pollution. Moreover, a high share of renewable power allows other significant advantages for the countries promoting these technologies, such as the improvement of the security of supply and the decrease of the energy dependency from other countries.

Nevertheless, as the most renewable technologies ultimately derive energy from unpredictable natural sources or sources that vary in their availability over different timescales, the integration of larger amounts of renewable energy raises some issues related to the power systems operation (IEA, 2005).

In this regard, the power demand and generation balancing becomes one of most important issues that result from the increasing integration of renewable sources. This issue will emerge especially in periods with high renewable generation and low demand and implies an action from the power system operator in order to maintain the system stability. Apparently, there are three different solutions to face the power demand and generation balancing; the first one is the curtailment of the renewable generation, resulting in a waste of this power source, the second one is to export power to an interconnected grid (Hammons, 2006), not disregarding the possibility of that grid being also submitted to the same power balance issue, and finally the third solution, that avoids the disadvantages of the preceding ones, is to store the excess of renewable power for use when it is needed, keeping the stability of the power grid (Barton & Infield, 2004 and Faias et al., 2007).

The concept of energy storage systems embedded in the power grid, which will be presented in the current chapter, allows decoupling partially the demand from the supply, facilitating the penetration of renewable sources and improving the flexibility and efficiency of the power grid. This concept will be applied to the Portuguese power system case, considering the predictions for the load and for the generation installed capacity, including renewable, for the year 2011.

The methodology used along this chapter begins with the description of the power unbalance between generation and demand issue and the solutions for its mitigation. After that, the available energy storage technologies are presented as well as the energy storage system design process. Following, a brief discussion on the different perspectives for the location of embedded energy storage system in the power grid is presented. Finally, the results for Portuguese power system case study are presented, analysed and discussed.

2. Balancing Power Demand and Generation

Traditionally the power system operation is based on the principle that at each moment in time the power demanded by the load is generated, at that moment, by the set of power plants in the system. For that reason, if either the demand or the generation experience a sudden and sharp increase or decrease, power unbalances would occur resulting in power system instability. As, in general, the power demand is not controlled by the power system operator, its action is focused on the power generation dispatching.

Power generation dispatch is also known as the unit commitment, and it consists of defining which power units should be operating at a specific moment and the power generated by each unit (dispatch) in order to satisfy the power demand.

Power demand varies along time and according to different drivers, such as seasonality, weather condition, geographical location and the society economic activity. Extreme weather temperatures usually induce a higher power demand. On the other hand, there is a reduction on the power demand during the night and during the weekends, as a result of lower industrial activity and people's specific daily routine. Figure 1 presents different time cycles variations imposed by each one of the causes referred above.
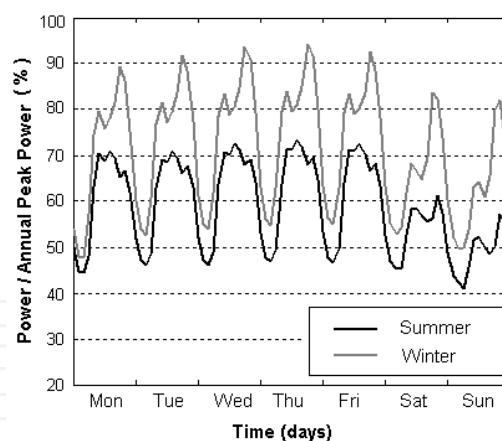

Fig. 1. Power demand variation along different time cycles (REN, 2008)

In the past, from the power system operator perspective, the uncertainly was mainly on the demand-side. However, the increasing integration of non-dispatchable renewable power sources results in an uncertainly that is also endogenous to the generation-side.

Renewable energy, which is dependent on natural resources like wind, rain and sun, present a much variable availability and can not be easily committed and dispatched by the power system operator. This variability of renewable power is apparent in Figure 2, where an example of the aggregated wind power generation along the period of one week is presented.
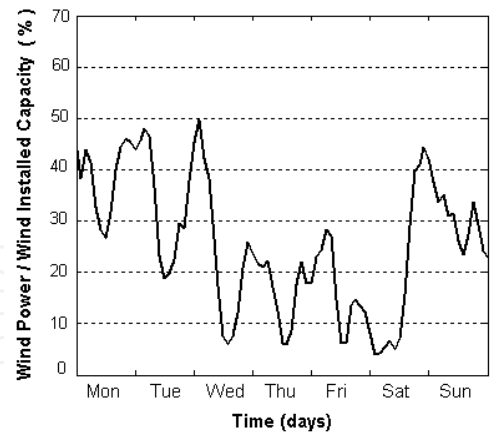
Fig. 2. Aggregated wind power generation along the period of one week (REN, 2008)

Therefore, the system operator usually considers the renewable generation as a negative power demand, satisfying the remaining demand through the unit commitment of the conventional (thermal and large hydro) power plants (Ortega-Vazquez & Kirschen, 2009).

2.1 Power Unbalance

Besides the power system operation constraints induced by the renewable power sources availability, there is an additional issue that should be taken into account. This issue is the power unbalance between power generation and demand, resulting from the coincidence of the higher availability of renewable sources (wind power, for instance) with the periods of lower demand. This fact is confirmed in Figure 3, where the equivalent average day of an annual aggregated wind power generation and the average day of an annual aggregated power demand are compared.
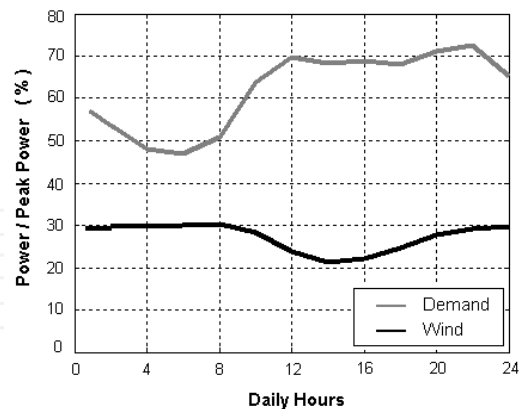

Fig. 3. Comparison between the equivalent average day of an annual aggregated wind power generation and the equivalent average day of an annual aggregated power demand (REN, 2008)

The coincidence of the wind peak power with the demand off-peak power may origin some moments where the non-dispatchable generation is greater than the demand. The resulting power unbalance can be characterized by:

$$P_{Unb}(t) = P_{Gen}(t) - P_{Dem}(t) \tag{1}$$

where $P_{Unb}(t)$ is the power unbalance, $P_{Gen}(t)$ is the power generated and $P_{Dem}(t)$ is the power demand, at time t.

Positive power unbalances correspond to an excess of generation, while negative power unbalances correspond to a generation shortage.

Positive power unbalances can occur in power systems with high penetration of non-dispatchable renewable power sources, like wind power. High hydro power availability and the minimal spinning reserve of the thermal power units also contribute to the occurrence of positive power unbalances.

Negative power unbalances only occur in moments when the available power capacity is not enough to cover all the power demands needs.

2.2 Solutions for Power Unbalance Mitigation

In practice no power unbalances should occur in a power system, otherwise, it would not be possible to the power system operator to keep the system in perfect operation and maintaining the standard power quality levels.

In moments when the power system tends to be unbalanced, namely driven by an increasing renewable power generation, the power system operator must act in order to mitigate that power unbalance and its consequences.

Following, it is presented a sort of solutions that can be adopted, individually or complementarily, to mitigate the power unbalance issue, such as curtailment of renewable generation, interconnections with other power systems and energy storage

(a) Curtailment of renewable generation

The curtailment of renewable generation is one of the possible solutions to avoid unbalances between power generation and power demand. Such solution consists of an order emitted by the power system operator to the renewable power producers to cut partially or totally their generation.

Renewable generation curtailment usually implies the waste of an environmental friendly natural resource and an increase on the fossil fuels consumption. As so, this power unbalance mitigation solution should only be considered in case of extreme contingencies.

(b) Interconnections with other power systems

Strong interconnections between different power systems are today an important advantage in terms of energy management and compensation of local power unbalances (Hammons, 2006).

The recent increasing integration of renewable power sources has been one of the drivers to reinforce the interconnection capacity of the power grids, enabling each country or region to best exploit the endogenous renewable resources creating together a diversified generation mix.

In spite of the interconnection between different power systems being one of the best solutions to mitigate the power unbalance, there are some constraints to its application, namely the one related to the potential of existing simultaneous power unbalances in the interconnected regions.

(c) Energy storage

Energy storage offers additional benefits in utility settings because it can decouple demand from supply, thereby mitigating the unbalances on the power system and allowing increased asset utilization, facilitating the penetration of renewable sources, and improving the flexibility, reliability, and efficiency of the electrical network (Schoenung, 1996).

The option for energy storage solution involves an investment on an energy storage system, but, on the other hand, it avoids the disadvantage of the renewable power curtailment and the constraints related to exporting power through the grid interconnections.

3. Energy Storage Technologies

Today, there are several high performance storage technologies available or at an advanced state of development, demanded by a new range of the energy storage applications. The singularities of each storage technology, dependent on their operation fundamentals, turn it unique and difficult to compare them.

A typical method used for the storage technology comparison, based on the power and energy capacities of commercialized devices, is presented as example in Figure 4. This power and energy range comparison of the technologies allows the identification of the devices that are best suited for a specific application.
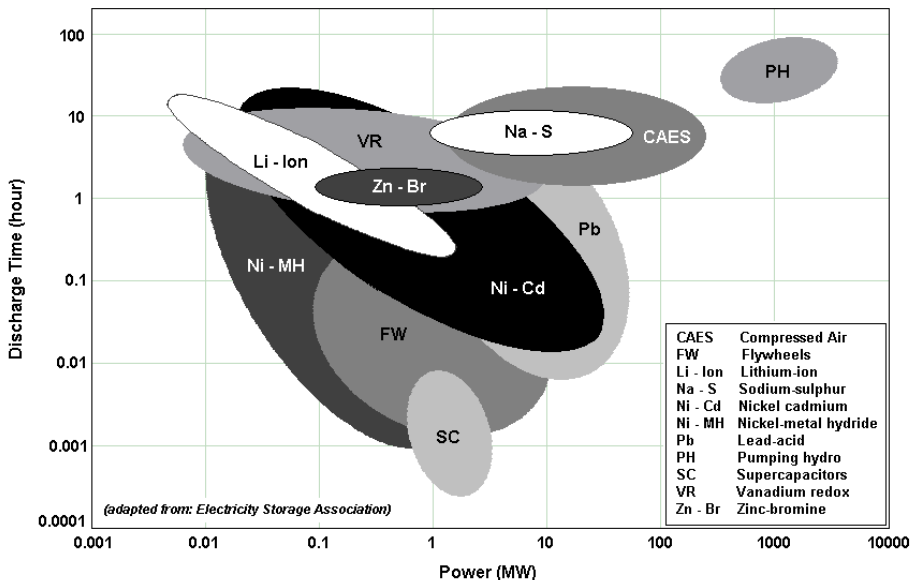

Fig. 4. Power and energy capacity comparison for different energy storage technologies (ESA, 2009)

In order to best distinguish the energy storage technologies applications and considering their placement on the ordinates axe of the figure above, storage technologies are here classified into two different categories, based on their discharge time. These categories are: short-term discharge energy storage devices and long-term discharge energy storage devices.

Short-term discharge energy storage devices present a very fast response to the power system needs. However, they just can supply their rated power for short periods, which

vary from milliseconds to few minutes. The short-term discharge energy storage devices are usually applied to improve power quality, to cover load during start-up and synchronization of backup generators and to compensate transient response of renewable power sources (Tande, 2003).

Long-term discharge energy storage devices are able to supply power from some seconds to many hours. Their response to the power system needs is usually slower than the short-term discharge energy storage devices, and much dependent on the technology. Long-term discharge energy storage devices are usually applied on the energy management, renewable energy sources integration and power grid congestion management (Price et al., 1999).

3.1 Short-term discharge energy storage devices

Short-term discharge energy storage devices should be used to aid power systems during the transient period after a system disturbance, such as line switching, load changes and fault clearance. Their application prevents collapse of power systems due to loss of synchronism or voltage instability, improving its reliability and quality.

Short-term discharge energy storage devices use is getting common in power systems with important renewable energy penetration (like wind, for instance) and weak interconnections or in islands, avoiding temporary faults and contributing to the provision of important system services such as momentary reserves and short-circuit capacity (Hamsic et al., 2007).

The main short-term discharge energy storage devices and their operation are presented below.

(a) Flywheels

Flywheels store kinetic energy in a rotating mass. Such equipments have typically been used as short-term energy storage devices for propulsion applications such as powering train engines and road vehicles, and in centrifuges. In these applications, the flywheel smoothes the power load during deceleration by dynamic braking action and then provides a boost during acceleration (Lazarewicz and Rojas, 2004). Figure 5 presents the operating diagram of a flywheel energy storage system.
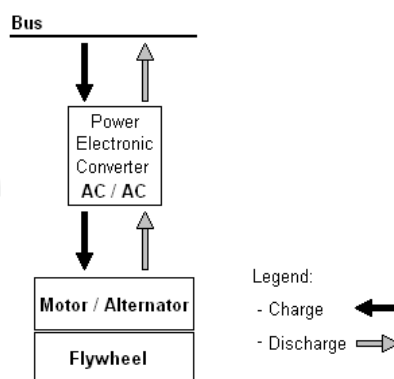

Fig. 5. Flywheel energy storage device operation diagram

(b) Supercapacitors

Supercapacitors are the latest innovative devices in the field of electrical energy storage. In comparison with a battery or a traditional capacitor, the supercapacitor allows a much powerful power and energy density (Zhai et al., 2006).

Supercapacitors are electrochemical double layer capacitors that store energy as electric charge between two plates, metal or conductive, separated by a dielectric, when a voltage differential is applied across the plates (Rufer et al., 2004). As like battery systems, capacitors work in direct current. This fact imposes the use of electronic power systems, as presented in Figure 6.
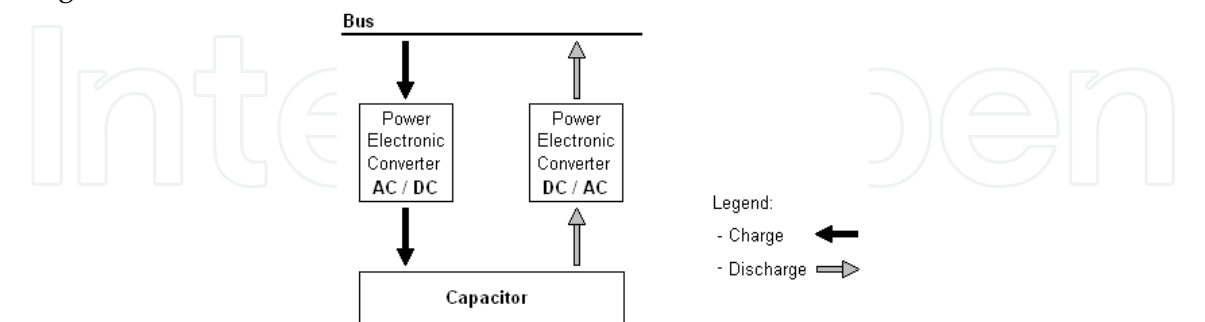

Fig. 6. Supercapacitor energy storage device operation diagram

(b) Magnetic Superconducting

Superconducting magnetic energy storage devices store energy in the form of a magnetic field, through a direct current flowing in a superconducting coil. The alternate current from a power bus is converted to direct current and injected in the coil. When necessary, the stored energy can be released, through a direct current that is converted to alternate current and injected in the power bus (Hsu and Lee, 1992). The interface between the power bus and the superconducting coil uses power electronic converters (Nomura et al., 2006).

The Superconducting Magnetic Energy Storage (SMES) device operation diagram is presented in Figure 7.
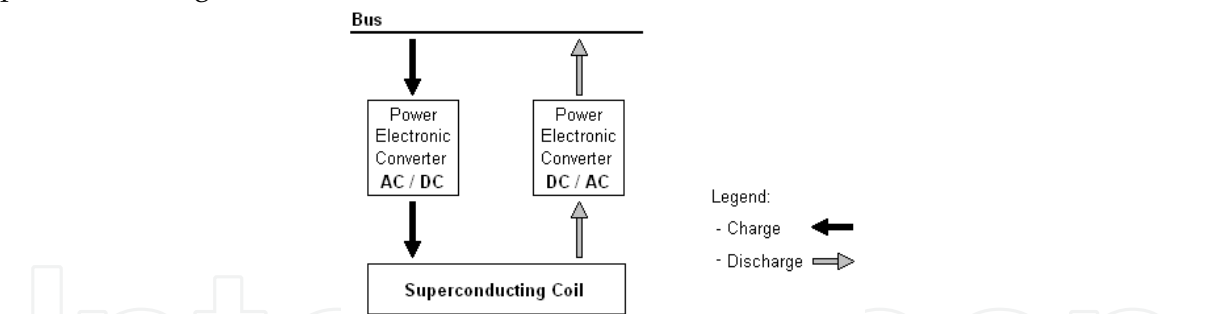

Fig. 7. SMES device operation diagram

The conductor for carrying the direct current operates at cryogenic temperatures where it behaves as a superconductor and thus has virtually no resistive losses as it produces the magnetic field. Consequently, the energy can be stored in a persistent mode, until required. The most important advantage of SMES device is that the time delay during charge and discharge is quite short. Power is available almost instantaneously and very high power output can be provided for a brief period of time (Mito et al., 2004).

3.2 Long-term discharge energy storage devices

The so-called long-term discharge energy storage devices have the capability to supply or absorb electrical energy during hours.

Sort of different long-term discharge energy storage technologies are already available today and their use is expected to rise in the next years because of the increasing integration of non-dispatchable renewable energy generation in the power systems (IEA, 2005).

A brief description of the main long-term discharge energy storage technologies is presented below.

(a) Pumping Hydro

In pumping hydro energy storage, a body of water at a relatively high elevation represents a potential or stored energy. When generation is needed, the water in the upper reservoir is lead through a pipe downhill into a hydroelectric generator and stored in the lower reservoir. To recharge the storage system, the water is pumped back up to the upper reservoir and the power plant acts like a load as far as the power system is concerned.

Pumping hydro energy storage system is constituted by two water reservoirs, an electric machine (motor/generator) and a reversible hydro pump-turbine unit. The system can be started-up in few minutes and its autonomy depends on the volume of stored water.

There are three possible configurations for the pumping hydro systems. The first one, the pure pumping hydro, corresponds to a power plant that is specifically set-up for storage, where the only turbinated/pumped water is the one stored in the upper and lower reservoirs. The second configuration corresponds to a reservoir hydro power plant, integrated in a river course, equipped with a lower reservoir and a reversible pump-turbine unit. The third configuration corresponds to a cascade of hydro power plants, where some reservoirs act simultaneously like upper and lower reservoir for the different power plants. In second and third configurations, the most common, the power plant operation is more complex because of the coordination of the different power plants and the reservoir inflows resultant from the river.

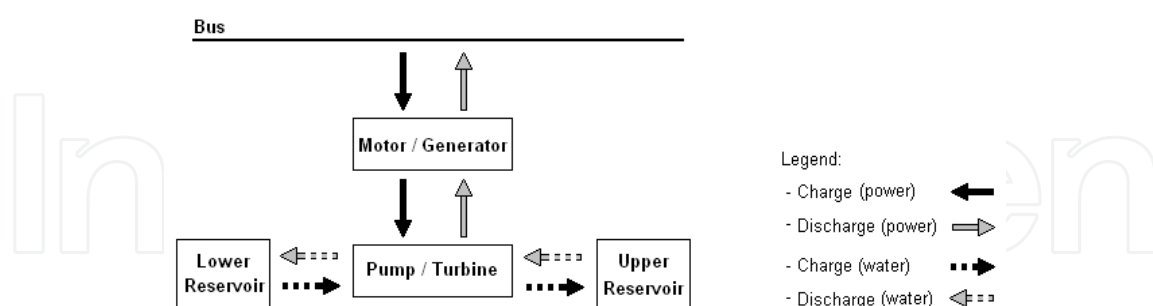The operation of a pumping hydro system is presented in Figure 8.

Fig. 8. Pumping hydro system operation diagram

Pumping hydro energy storage system operation is constrained by the weather conditions, reducing its storage capacity in periods extremely wet or dry.

The main restrictions to pumping hydro energy storage implementation are related with geographical constraints.

(b) Batteries
Batteries store energy in electrochemical form creating electrically charged ions. When the battery charges, a direct current is converted in chemical potential energy, when discharges, the chemical energy is converted back into a flow of electrons in direct current form (Hunt, 1998). The connection of the system to the grid, as presented in Figure 9, implies the use of power electronic converters in order to rectify the alternate current during the battery charge periods and to invert the direct current during the battery discharge periods.
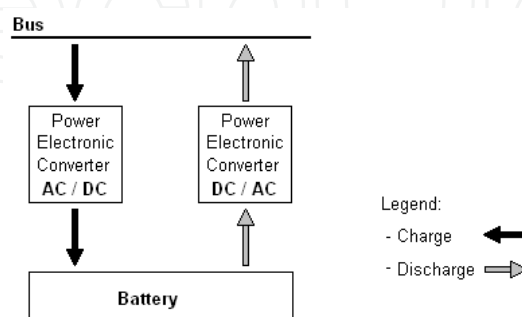

Fig. 9. Battery device operation diagram

Batteries are the most popular energy storage devices. However, the term battery comprises a sort of several technologies applying different operation principals and materials. As so, the distinction between two important battery concepts, electrochemical and redox-flow, is hereby emphasized.

Electrochemical
Electrochemical batteries use electrodes both as part of the electron transfer process and store the products or reactants via electrode solid-state reactions (Price et al., 1999).
There are a number of battery technologies under consideration for energy storage, the main being:
- Lead acid
- Nickel cadmium
- Nickel metal-hydride
- Sodium sulphur
- Lithium ion

Redox-Flow
Redox-flow batteries are storage devices that convert electrical energy into chemical potential energy by charging two liquid electrolyte solutions and subsequently releasing the stored energy during discharge (Ponce de León et al., 2006).
The name redox-flow battery is based on the redox reaction between the two electrolytes in the system. These reactions include all chemical processes in which atoms have their oxidation number changed. In a redox flow cell the two electrolytes are separated by a semi-permeable membrane. This membrane allows ion flow, but prevents mixing of the liquids. Electrical contact is made through inert conductors in the liquids. As the ions flow across the membrane, an electrical current is induced in the conductors (EPRI, 2007).

Over the past few years three types of redox-flow batteries had been developed up to the stage of demonstration and commercialization. These types are vanadium redox batteries (VRB), the polysulphide bromide batteries (PSB) and the zinc bromine (ZnBr).

(c) Compressed air

Compressed air energy storage is a device based on as gas turbine where the compression and the combustion processes are divided. During charging, the compressor is coupled to the electrical machine, working as a motor, compressing the air. After the compression, the air is stored into a sealed underground cavern. Discharging the device consists in generating power through the coupling of the gas turbine with the electrical machine, working as generator, and supplying the stored compressed air to the combustion process (Lerch, 2007). A compressed air energy storage system operation diagram is presented in Figure 9.
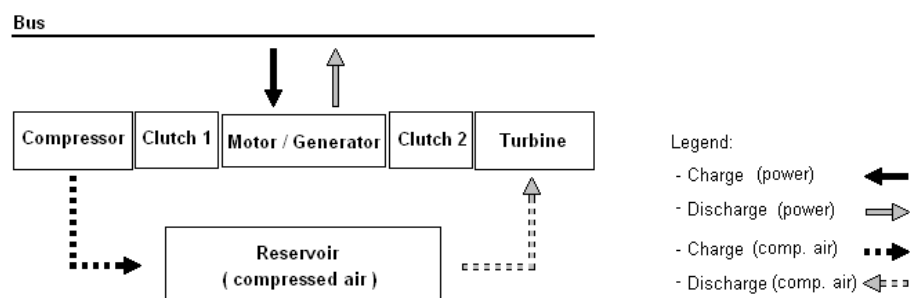

Fig. 9. Compressed air energy storage system operation diagram

Three air reservoir types are generally considered: naturally occurring aquifers (such as those used for natural gas storage), solution-mined salt caverns, and mechanically formed reservoirs in rock formations. Main compressed air energy storage system implementation constraints are related with reservoirs achievement (Schoenung, 1996)

(d) Hydrogen fuel cell

A fuel cell is an energy conversion device that is closely related to a battery. Both are electrochemical devices for the conversion of chemical to electrical energy. In a battery the chemical energy is stored internally, whereas in a fuel cell the chemical energy (fuel and oxidant) is supplied externally and can be continuously replenished (Hoogers, 2003).

The overall reaction in a fuel cell is the spontaneous reaction of hydrogen and oxygen to produce electricity and water. During the operation of a fuel cell, hydrogen is ionized into protons and electrons at the anode, the hydrogen ions are transported through the electrolyte to the cathode by an external circuit (load). At the cathode, oxygen combines with the hydrogen ions and electrons to produce water.

The hydrogen fuel cell system can be reversible, allowing electric power consumption for the production of hydrogen and that hydrogen can be stored for later use in the fuel cell (Agbossou, 2004).

The operation diagram of a hydrogen fuel cell energy storage system is presented in Figure 11.

Hydrogen volatility and its atoms reduced dimension put the hydrogen storage reservoir as the critical element in this device. Last research place Metallic Hydrates as one of most efficient (Ogden, 1999).

In the last years, hydrogen fuel cell systems become one of the most referred storage technologies to set up renewable energy integration issue. Price and charge/discharge efficiency about the 30% are its main constraints.
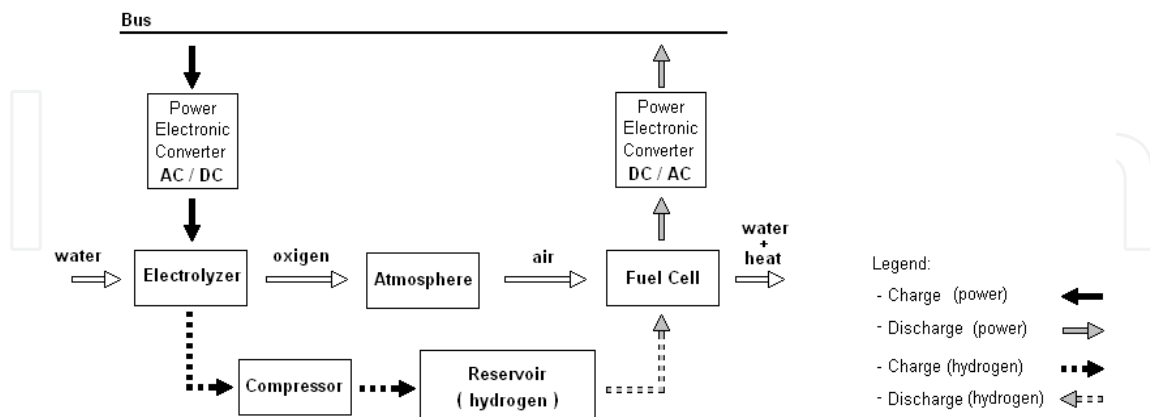

Fig. 11. Hydrogen fuel cell energy storage system operation diagram

4. Energy Storage System Design

The energy storage system design process consists off the determination of the storage power and energy capacity and the technologies that allow a better integration of the renewable sources of energy and the minimization of the thermal units fuel consumption and greenhouse effect gaseous emissions.

The energy storage system design process is divided in two different phases. The first phase consists of the implementation of an unit commitment, including the energy storage system, in order to enable the technical evaluation of several power and energy storage capacity combinations and optimize their operation. Besides the operation optimization and the feasibility evaluation of each power and energy storage capacity combination, in the first phase of the design process are also determined the needs for renewable energy curtailment and the total thermal power units operation cost.

The second phase of the energy storage system design process is based on an economical evaluation, where the costs and benefits associated to each technically feasible power and energy storage capacity combination are considered and the best techno-economical energy storage solution is determined.

4.1 Optimization of the energy storage system operation

The energy storage system operation, along a time-series, is determined throughout an optimization process that manages the system in order to best integrate the renewable energy generation, allowing, consequently, a minimization of the thermal power plants costs. The thermal power plants costs are computed by adding up the fuel costs with the emission costs due to CO_2.

The optimization process is based on a power plant commitment problem, where the load, the renewable generation and the interconnections with other power grids are considered as input data, forecasted in a previous process. The energy storage system is integrated and operated as an additional power generation unit. The specificity of that unit is related to its ability to absorb power, especially in moments when the power system has no capacity to

accommodate all the renewable generation. A negative power of that power generation unit corresponds to charging the storage system and a positive power corresponds to its discharge.

The power and energy limits of the energy storage system are imposed and considered as an input of the optimization problem. Therefore, it may be possible that, for some moments of the time series, the need for power storage overloads the storage capacity, and renewable power generation must be curtailed. In order to quantify the global renewable power and energy curtailed, a power unit that represents the excess of renewable generation is considered.

The main objective of the energy storage system implementation is to support the integration of the renewable generation, being available to that integration as long as possible. For that reason, a penalty on the cost function has been introduced for the use of the storage system power charging, avoiding the temptation of the optimization process to exploit that system to attain the cheapest thermal power plants operation, when their minimal technical limits do not allow it. The penalty on the cost function does not affect the energy storage system negative power, enabling the system to be discharged anytime it is necessary or advantageous to avoid thermal power generation costs.

The curtailment power has also a penalty in the cost function, greater than the energy storage system charging one, enabling its use only when it is strictly necessary.

The objective function that is intended to be minimized considers the penalties presented above and the variable costs of the thermal power units, corresponding to their fuel costs and externalities resulting from the greenhouse effect gaseous emissions. Next, one presents the objective function:

$$\min z: \quad \sum_{t=1}^{T} \left[\delta_1 \times C^{ESS} \times P^{ESS}(t) + C^{Ctm} \times P^{Ctm}(t) + \sum_{j=1}^{J} C_V^j \times \tau \times P^j(t) \right] \tag{2}$$

where T is the total time series period, τ is the time interval between t and $t+1$, J is the number of thermal power units, $P^j(t)$ is the power generated by the thermal power unit j at moment t, C_V^j is the variable cost of generated energy of the thermal power unit j, $P^{Ctm}(t)$ is the renewable power curtailment at moment t, C^{Ctm} is the renewable power curtailment penalty (<0), $P^{ESS}(t)$ is the power of the energy storage system at moment t, C^{ESS} is the power charging penalty of the storage system (<0), finally δ_1 is used to distinguish positive and negative energy storage system power:

$$\delta_1 = \begin{cases} 0, & P^{ESS}(t) > 0 \\ 1, & P^{ESS}(t) \le 0 \end{cases}$$

The balance between the power demand and the power generation is maintained by the following equation:

$$P^{ESS}(t) + P^{Ctm}(t) + \sum_{j=1}^{J} P^j(t) = (1 + l_{AV}) \times L(t) - Q(t) \tag{3}$$

where $L(t)$ is the load power at moment t, $Q(t)$ is the sum of the renewable and the interconnections power and l_{AV} is the average value of the losses in the power network.

The commitment of the power units must consider the spinning reserve as presented in the next restriction:

$$P_{Max}^{ESS} + \sum_{j=1}^{J} P_{Max}^{j} \times v^{j}(t) \geq (1 + l_{AV}) \times L(t) - Q(t) \tag{4}$$

In (4) P_{Max}^{j} is the maximum power generated by the thermal power unit j, $v^{j}(t)$ is a binary variable that indicates, at moment t, if the thermal power unit j is running or if it is inactive. The term P_{Max}^{ESS} corresponds to the maximum discharging power of the energy storage system.

Considering the increasing integration of the wind power generation on the power systems and taking into account the volatility of that renewable energy source, there are some restrictions, introduced by the power systems operators, to the share of the wind power in the load power satisfaction. Therefore, in the moments when the wind power generated overcomes the level considered safe by the power system operator, the excess of wind power must be stored and the thermal power generation must be increased in order to fit the power demand. The following restriction reflects that concern:

$$\sum_{j=1}^{J} P^{j}(t) \geq \delta_{2} \times \left[(1 + w_{Max}) \times (1 + l_{AV}) \times L(t) - Q(t) + W(t) \right] \tag{5}$$

where w_{Max} is the maximum share of wind power admitted by the power system operator, $W(t)$ is wind power generated at moment t, and δ_{2} distinguish the moments when the maximum share of wind power is overloaded:

$$\delta_{2} = \begin{cases} 0, & W(t) \leq w_{Max} \times (1 + l_{AV}) \times L(t) \\ 1, & W(t) > w_{Max} \times (1 + l_{AV}) \times L(t) \end{cases}$$

In power system generation scheduling, the reflection of actual operating processes needs the use of ramp-rate constraints to simulate the thermal unit generation changes (Wang & Shahidepour, 1993). The thermal power units ramp-rates are considered and imposed by restrictions (6) and (7), corresponding to the ramp-up power rate and to the ramp-down power rate, respectively. No ramp-rates had been considered for the ESS.

$$P^{j}(t) - P^{j}(t-1) \leq P_{up}^{j} \tag{6}$$

$$P^{j}(t-1) - P^{j}(t) \leq P_{down}^{j} \tag{7}$$

where P_{up}^{j} and P_{down}^{j} correspond to the ramp-up power rate and to the ramp-down power rate of the thermal power unit j.

The limits to maximum and minimal power generation of each power unit are restricted by the conditions below:

$$P^{j}(t) \leq P_{Max}^{j} \times v^{j}(t) \tag{8}$$

$$P^j(t) \geq P^j_{Min} \times v^j(t) \tag{9}$$

In (9) P^j_{Min} corresponds to the technical minimum power that can be generated by the thermal power unit j.

The energy storage system operation is limited by:

$$P^{ESS}(t) \leq P^{ESS}_{Max} \tag{10}$$

$$P^{ESS}(t) \geq P^{ESS}_{Min} \tag{11}$$

The P^{ESS}_{Max}, as already referred, is the maximum discharging power of the storage system, and the P^{ESS}_{Min}, corresponds to the its maximum charging power (negative), or, alternatively, to the energy storage system minimum power.

The renewable curtailment power intervention just makes sense when the energy storage system has no ability to absorb more renewable power generation. Therefore, as presented in (13), its value is never positive.

$$P^{Ctm}(t) \leq 0 \tag{13}$$

As referred above, the storage system power and energy capacity are imposed and act like inputs of the problem. In the restrictions (10) and (11), the energy storage system power limits had been presented, and, next, one presents restrictions related to its stored energy limits.

The stored energy at each moment of the time-series results from the integral of the energy storage system power in the preceding moments, and can be determined by the following equation:

$$E^{ESS}(t) = E^{ESS}(t-1) - \tau \times P^{ESS}(t) \times \left[\delta_1 + (1-\delta_1) \times \frac{1}{\eta_{ESS}} \right] \tag{14}$$

In (14) $E^{ESS}(t)$ is the stored energy in the storage system at moment t, and η_{ESS} corresponds to the energy storage system charge/discharge power efficiency.

The stored energy in the storage system is limited by restrictions (15) and (16).

$$E^{ESS}(t) \leq E^{ESS}_{Max} \tag{15}$$

$$E^{ESS}(t) \geq E^{ESS}_{Min} \tag{16}$$

where E^{ESS}_{Max} and E^{ESS}_{Min} correspond to the maximum and minimum stored energy, respectively.

Imposing that the initial state-of-charge of the energy storage system must be the same as at the end of period T, it comes:

$$\sum_{t=1}^{T} P^{ESS}(t) \times \left[\delta_1 + (1-\delta_1) \times \frac{1}{\eta_{ESS}} \right] = 0 \qquad (17)$$

Once considered all the restrictions of the problem, the minimization of the objective function, because of the on-off solution for the thermal power units, can be provided by a mixed integer programming (Gollmer et al., 2000).

4.2 Cost of the energy storage system

The costs associated with the acquisition of an energy storage system are much diversified and dependent on the technology adopted.

The total energy storage system acquisition cost is composed by two different contributions; the contribution associated with peak power capacity of the storage device and the contribution associated to the amount of energy that can be stored. In Figure 12 a comparison of the acquisition costs for the commercialized energy storage technologies is presented.
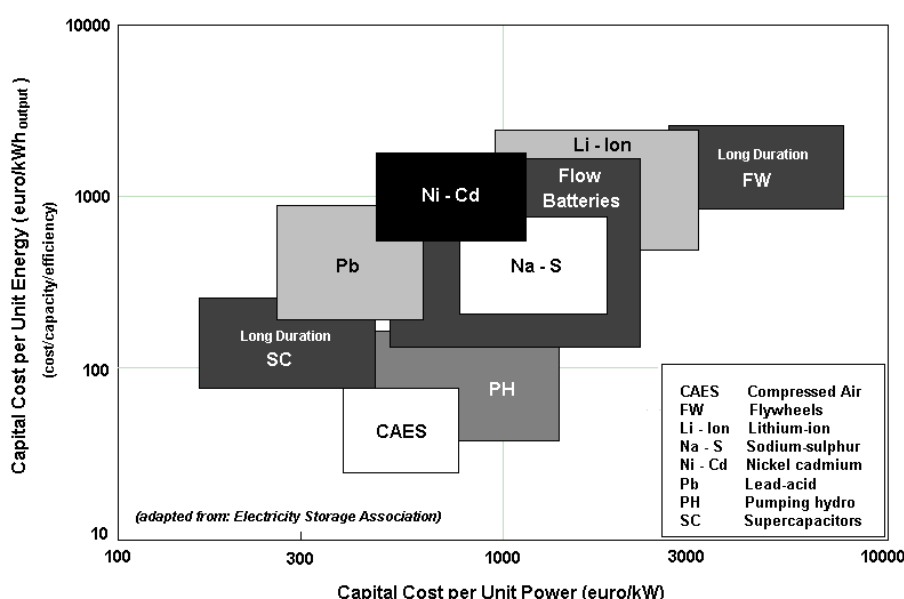

Fig. 12. Capital cost for the acquisition of different energy storage technologies (ESA, 2009)

The long-term discharge technologies applicable at large storage systems, like pumping hydro, compressed air or flow batteries, present a low dependency between the energy storage capacity and the peak power. In those cases, the capital cost for the energy storage device acquisition can be expressed as the sum of the power capital cost with the energy capital cost (Barton & Infield, 2004 and Chacra et al., 2005):

$$C^{ESS} = a_d \times P_{max}^{ESS} + \beta_d \times E_{max}^{ESS} \qquad (18)$$

where a_d is the capital cost per unit power of the technology d and β_d is the capital cost per unit energy of the technology d.

Variable costs associated to the energy storage system operation and maintenance are not considered in the present work.

Considering that the investment on the energy storage system acquisition can be amortized along its lifetime, it comes (Riggs et al., 1998):

$$C^{ESS} = \sum_{n=1}^{N} \frac{A^{ESS}}{(1+i)^n}$$

(19)

where C^{ESS} is the initial investment on the energy storage system acquisition, n is one of the years from the total lifetime N, A^{ESS} is the constant annual amortization of the initial investment and i is the interest rate.

Developing the series (19), comes:

$$C^{ESS} = A^{ESS} \left[(1+i)^{-1} + (1+i)^{-2} + \ldots + (1+i)^{-N+1} + (1+i)^{-N} \right]$$

(20)

Manipulating (20), the constant annuity A^{ESS} can be obtained by:

$$A^{ESS} = C^{ESS} \frac{i(1+i)^N}{(1+i)^N - 1}$$

(21)

Annuity A^{ESS} should be computed for each energy storage solution achieved and used for its economical evaluation.

5. Location of the Energy Storage Systems in the Power Grid

The implementation of the energy storage systems on the power grid allows a better management of the power flows due to the partial decoupling of the power demand and generation.

Through the energy storage use it is possible to absorb the excess of renewable generation that occurs during the off-peak periods and inject that stored energy into the grid during peak hours, avoiding the operation of the most expensive and pollutant power thermal units.

The carefully chosen location of the energy storage systems in the power grid can avoid non-desired power flows or congestions, improving the flexibility and the efficiency of the power grid.

Following, three different perspectives about the power grid energy storage systems location are presented and discussed.

5.1 Distributed energy storage at generation

The concept of distributed energy storage at generation considers that the energy storage systems are located near the most important non-dispatchable renewable power producers, such as the wind farms. Distributed energy storage at generation is the most intuitive perspective, because it mitigates the power unbalance issue at the original source.

In fact, as far as energy management is concerned, the distributed energy storage at generation perspective is as suitable as any other approach. However, from this energy

storage location, a considerable contribution in terms of global power grid congestions reduction is not expected. In this case, the energy storage systems are located near the renewable power generation and considering that the positive unbalance is prominent during off-peak hours, the stored energy is discharged into the system, leading to an increase of the power flows when the grid is eventually already congested.

One of the advantages of the distributed energy storage at generation is related to the possibility of downsizing the equipment used for the connection of the renewable producers to the power grid. This is due to the contribution of the energy storage system for the modulation of the renewable generation shape, enabling a less variable power output and avoiding the power peaks.

The implementation of distributed energy storage at generation depends on the availability of modular long-term discharge energy storage devices adapted to the specific characteristics of each renewable power plant (Faias et al., 2008).

5.2 Distributed energy storage at demand

Distributed energy storage at demand is a concept that considers the energy storage devices located near the demand, eventually in the interface between the transmission and distribution networks.

Distributed energy storage at demand promotes power flows at off-peak periods and relieves the system from power flows at peak periods. As the energy storage devices are disposed close to the regions where the energy is going to be consumed, the power grid congestions can be avoided, because the power flows between the renewable energy producers and the energy storage system is going to occur mainly during the off-peak periods. During peak hours, when the energy storage system is discharged, the power loads are partially supplied by that power and the needs for high power flows on the transmission network will be reduced.

Like the distributed energy storage at generation concept, the distributed energy storage at demand concept implies the use of modular medium-size long-term discharge energy storage devices.

5.3 Centralized energy storage

The concept of centralized energy storage is based on the idea of installing some (few) large energy storage devices on the power system in order to better manage the power unbalances induced by the increasing integration of the renewable power sources.

It is expected that the energy storage, being centralized in a small number of devices, does not contribute for an improvement on the power flows and congestions for all power grid topologies, because the power flows resulting from the excess of renewable generation will converge to the places where the centralized energy storage devices are located. In addition, during the discharge periods, the power flows on the energy storage devices neighbourhood are also going to rise, increasing the congestions and resulting in a potential negative contribution for the overall power system efficiency.

The main centralized energy storage advantages come from the energy storage technologies that can be applied as far as this concept is concerned. Large-size long-term discharge energy storage devices like pumping-hydro and compressed air are best suited for this kind of centralized application. These technologies present the lower capital costs per power and

energy units. Despite the geographical constraints associated to each one of these storage devices, as the number of units to be implemented is small, it is not expected that it would be much difficult to find some location presenting adequate physical conditions for their installation.

6. Case Study: Portuguese Power System at 2011

The case study hereby presented corresponds to the Portuguese power system, which has experienced an increasing integration of renewable power sources during the last years.

The currently installed capacity in Portugal is about 15 GW and comprises coal (12%), natural gas (15%), fuel oil (11%) and diesel fuel utilities (1%), referred as thermal technologies; reservoir (16%) and run-of-river (14%), referred as hydro with more than 10 MW; cogeneration (6%), wind (18%), small hydro that account for less than 10 MW (2%), biomass (2%), municipal solid waste (0.6%) and photovoltaic (0.4%), referred as renewable (REN, 2008).

2008 was a year in which hydro generation presented a value 44% lower than the usual. That is why the renewable generation was only about 27% of the consumed energy. The main contributors for the renewable generation were the hydro power (12%), the wind power (11%) and the biomass (4%). For the year 2010, Portuguese authorities estimate that the renewable generation will correspond to 45% of the consumed energy.

Wind power is the renewable source of energy that has experienced the highest increase in the Portuguese power system. At the end of the year 2008, the wind power installed capacity was about 2800 MW, 11 times higher than at the 2003. According to the national power system operator predictions, by year 2010, wind power will correspond to 25% of the installed capacity.

As already referred in this chapter, such significant share of a variable and non-dispatchable renewable power source could induce some problems related to the power system unbalance. In the sequence, one presents an evaluation of the power unbalance issue in the Portuguese power system, by year 2011, and discusses possible solutions for that problem.

6.1 Power unbalance forecast

The power unbalance forecast intends to evaluate the impact of the increasing integration of renewable power sources, namely wind power, in the power unbalance between generation and demand on the Portuguese power system by year 2011.

The forecast procedure is based on the Portuguese power system historic data of 2007 by power plant and by aggregated demand buses at transmission level.

Forecasts for the demand, renewable generation and interconnections with other power grids use the historic data adjusted to the predicted installed capacity and energy consumption by the year 2011.

Thermal power generation predictions have been computed using the above mentioned (section 4.2) thermal unit commitment methodology, based on the power demand needs and considering the fuel and pollutant emissions costs. Thermal power spinning reserve was determined also through the historic data analysis. An average power grid losses value have been also considered and added to the power demand.

Therefore, considering all conditions referred above, the power unbalance had been forecasted and the obtained results are presented in Figure 13.

Forecast results show that the power generation will overcome the power demand during
25% of the year, corresponding to an energy equivalent to 9.5% of the annual wind power
generation. It is also possible to verify that, in selected moments, the power unbalance
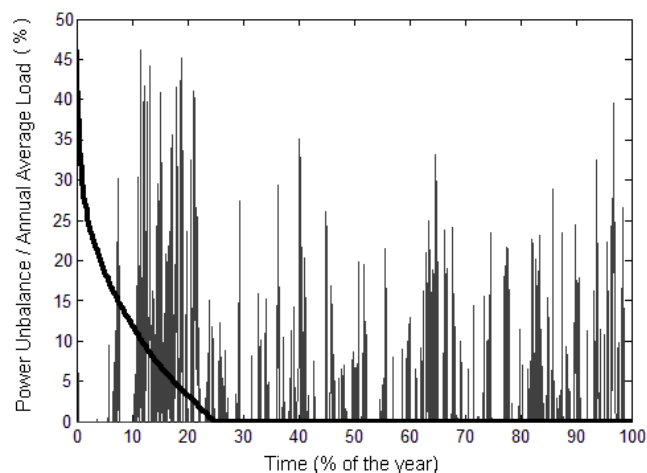reaches almost 50% of the annual average load.

Fig. 13. Time-series and duration curve of the power unbalance forecast (year 2011)

In order to better understand the hourly distribution of the power unbalance along the day,
the equivalent average day of the forecasted annual power unbalance time-series was
determined. The result is presented in Figure 14 where, as expected, the emphasis goes to
the power unbalance prominence during the off-peak hours. This fact results from the time
coincidence of the lowest power demand with the highest wind power availability.
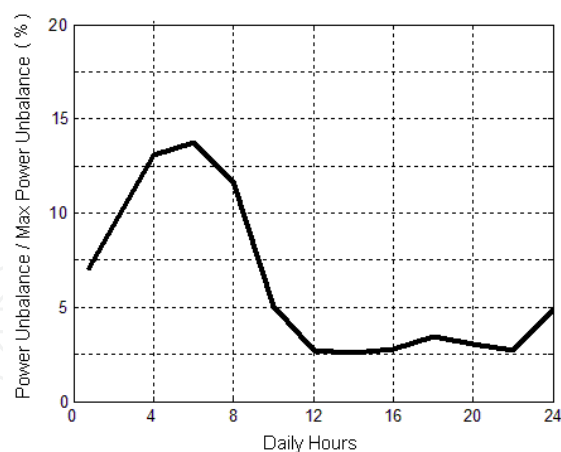

Fig. 14. Equivalent average day of the forecasted annual power unbalance

Regarding the excess of power generation estimated by the forecast and the need to mitigate
that power unbalance, two different, but complementary, solutions can be adopted. The first
one corresponds to the implementation of an energy storage system able to absorb the
excess of generation, and the second one, the curtailment of the wind power generation.
Taking into account that the renewable power generation should not be wasted because of
its several benefits, the wind power curtailment must be assumed as the last option.

The use of the interconnections with the Spanish power system is not considered as a solution to mitigate the power unbalance. Spanish power system also presents an important share of renewable energy, namely wind power, and probably the power unbalance issue affects similarly both power systems. Moreover, historic interconnection data shows that during the off-peak periods, when the forecasted power unbalance tends to be more intense, the fluxes of energy are typically from Spain to Portugal.

6.2 Energy storage system design

The energy storage system design follows the procedure previously described in section 4. Different power and energy combinations for the energy storage system are introduced in the unit commitment problem and their feasibility is evaluated. The economical benefit that result from the cost reduction of the fuel consumption and greenhouse gases emissions due to the lower renewable power curtailment are also computed during that procedure. Results are presented in Figure 15.

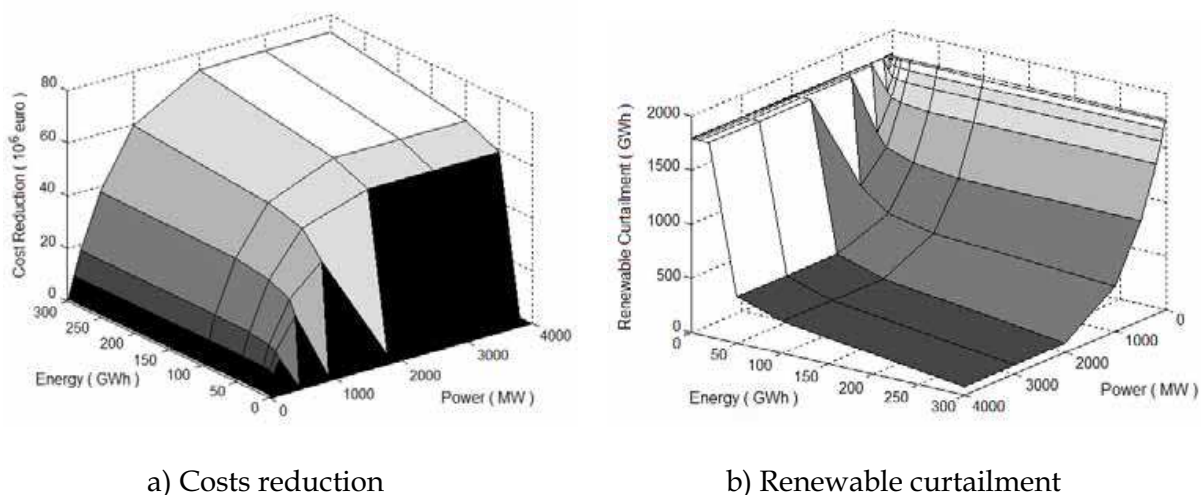a) Costs reduction   b) Renewable curtailment

Fig. 15. Impact of different power and energy storage combinations on the reduction of annual thermal power plants costs and on the curtailment of the renewable generation

The economical benefit resulting from the reduction of fuel consumption and greenhouse gases emissions due to the implementation of the energy storage system is directly proportional to the increment on the storage power and energy capacity, while it is inversely proportional to the need of renewable generation curtailment. The energy storage system able to completely match the power unbalance would need a global capacity of 3270 MW and 395 GWh.

Together with the thermal power plants economical benefits induced by the energy storage system, also the capital costs associated with the energy storage system acquisition must be considered. Therefore, the capital costs of the different technologies are deduced to the benefits that result from their implementation.

The net economic benefit was computed for the long-term discharge energy storage technologies like compressed air, pumping hydro and redox-flow batteries, assuming the interval between the maximum and minimum capital cost of the energy storage system acquisition (Figure 12) and an interest rate of 5%. The lifetime assumed for each technology was respectively 30 years, 40 years and 15 years (Schoenung et al., 1996) (EPRI, 2007).

Hydrogen fuel cell energy storage technology was not considered in this procedure due to its low charge/discharge efficiency.

From the three technologies considered, it was concluded that only compressed air energy storage presents some positive net economic benefits, when assuming the minimal value of the acquisition cost interval.

The best economic result corresponds to an annual benefit of 1.2 million euros for a 100 MW and 1500 MWh storage system. Despite the contribution of this storage system to the power unbalance mitigation, its small capacity forces a renewable generation curtailment equivalent to 8.6% of the annual wind power generation.

The solution that presents the second best economic result corresponds to a 50 MW and 500 MWh energy storage system and allows an annual benefit of 690000 euros. The renewable generation curtailment corresponding to this system is equivalent to 9% of the annual wind power generation.

An energy storage system of 200 MW and 5000 MWh capacity presents the third best economic result, allowing a benefit of 570000 euros and a renewable generation curtailment equivalent to 7.7% of the annual wind power generation. This system, from all the energy storage solutions with positive economic results, is the one that better absorb the power unbalance.

The 200 MW and 5000 MWh energy storage system operation along the period of one typical week, and its contribution for balancing the power generation and demand is presented in Figure 16.
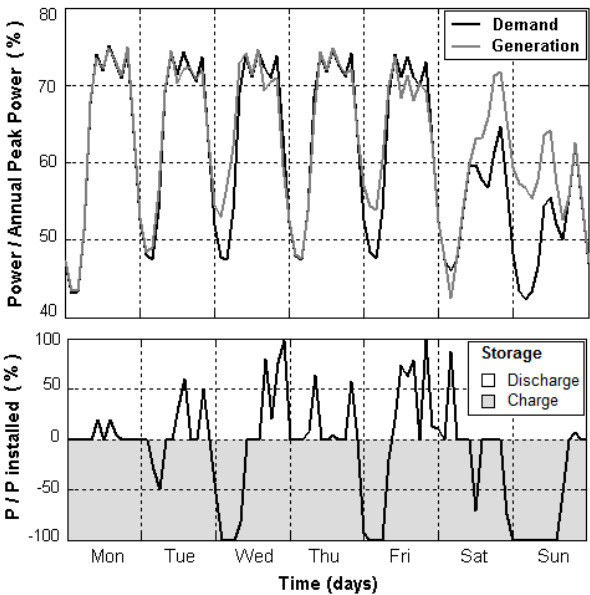

Fig. 16. Energy storage system (200 MW and 5000 MWh) operation and its contribution for balancing the power generation and demand along the period of one week

Through the analysis of the figure, it is possible to identify, during the off-peak hours, the moments when the energy storage is charging, in order to absorb the excess of power generation. Also the energy storage system discharging moments are easily identified, during the peak hours, when the energy storage system is contributing to avoid additional thermal power generation.

The results obtained from the energy storage system design procedure, applied to the Portuguese case study, lead to the conclusion that the economically viable solutions only enable the integration of a small percentage of the power unbalance induced by the renewable generation. However, it should be emphasized that assuming higher fuel and greenhouse gases emissions costs, as well as lower storage systems capital costs, the economic viability of larger integration of the power unbalance would be improved.

6.3 Power system with integrated pumping hydro

Some power systems with large amount of hydro installed capacity, such as the Portuguese system, comprise reversible hydro power plants with energy storage capacity that are usually used for the energy management improvement.

In the present scenario it is assumed that all of the pumping hydro installed capacity is available for helping the integration of the renewable power generation (in opposition to the previous scenario where the pumping hydro system was operated according to the historic data).

The estimated Portuguese pumping hydro capacity corresponds to 1051 MW and 25.2 GWh, and as far as the power unbalance forecast evaluation is concerned, it had been introduced in unit commitment problem as an additional energy storage system. As the Portuguese pumping hydro power plants are integrated in river flows, besides the usual constraints considered for all energy storage systems, an additional constraint was introduced to the pumping hydro operation, in order to consider the forced power discharges that result from the predicted up-side reservoir water inflows.

Therefore, the power unbalance forecast procedure had been applied assuming that the pumping hydro system is completely available to cooperate in the integration of the renewable generation. As expected, that availability results in a lower power unbalance, reducing the renewable curtailment need for a value equivalent to 4% of the annual wind power generation.

In order to evaluate the viability of an additional energy storage capacity for reducing the need for renewable power curtailment, the energy storage design process was again applied. Results show that, in this scenario, there is only one economically viable power and energy storage capacity combination. The energy storage system corresponds to a single compressed air energy storage unit with 10 MW, and 100 MWh. The annual net economic benefit of the energy storage system implementation is 780000 euros, and it is only viable assuming the minimum capital costs for the compressed air energy storage technology. The benefit introduced by this storage system, in terms of the integration of renewable power generation, is marginal. The renewable power generation curtailment, before the implementation of the energy storage system, was equivalent to 4% of the annual wind power generation, and after that it was 3.9%.

One of the objectives of the design process economical evaluation is to identify a particular energy storage system capacity and technology, however, the specificities of that technology should be carefully considered in order to validate its technical feasibility.

In Figure 17, where contribution of the two different energy storage systems for the power demand and generation balancing is presented, it is possible to follow the desired response for the compressed air energy storage system, referred as the other storage. Remembering that the compressed energy storage system operation is based on a gas turbine, difficultly it will respond to such demanding operation conditions.
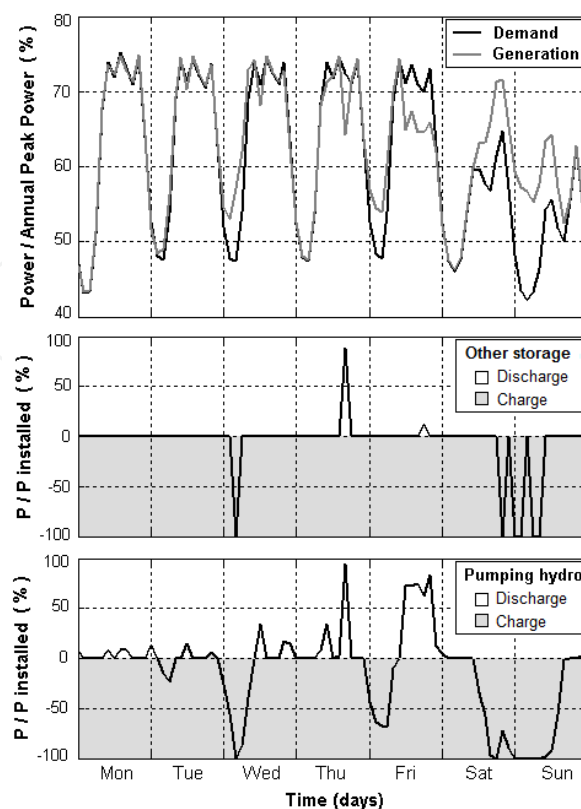
Fig. 17. Pumping hydro and the designed energy storage system operation and their contribution for balancing the power generation and demand along the period of one week

7. Conclusion

In the last years the world has assisted to an impressing development of the renewable energies, driven by the need for reducing negative environmental impacts that resulted from an intense exploitation of fossil fuels. Besides the environmental concern, as the renewable energy sources are endogenous to many countries, also the security of supply has been one of the key factors responsible for that development of the renewable energy.

The electricity generation sector, in particular, is the one that more intensely has experienced the replacement of fossil fuel based technologies by technologies that make use of renewable energy sources. As a result of that change, new challenges and issues have emerged on the operation of the power systems.

As most of renewable technologies ultimately derive energy from unpredictable natural sources or sources that vary in their availability over different timescales, balancing power generation and demand is one of the issues that is raised with an increasing integration of renewable energy in the power system. Balancing power generation and demand is an issue that occurs especially during the off-peak periods, when typically the power demand is lower and the non-dispatchable renewable power can become higher than the demand.

There are three different approaches to mitigate the power unbalance resulting from an excess of renewable power generation; curtailment of the renewable generation, interconnections with other grids and the energy storage. However, in order to avoid the waste of renewable generation and considering that different interconnected power systems

can be simultaneously with similar difficulties for balancing their systems, the use of an energy storage system seems to be the best suited solution.

At the moment, there are several energy storage technologies available for helping the integration of renewable energy sources in the power system. From those technologies one distinguishes among the pumping hydro energy storage, the compressed air energy storage and redox-flow batteries. Different technologies correspond to different power and energy capacity ranges and to different capital costs. Pumping hydro and compressed air energy storage systems present the larger power and energy capacity ranges and the lower investment costs. However, there are some restrictions to their implementation due to the need for specific geographical conditions. The modularity of the redox-flow batteries put great expectative in its use, nevertheless their investment costs make them few competitive at present.

An energy storage system design methodology had been developed along the present chapter. The main goal of this design methodology was to choose an energy storage system able to integrate as much renewable generation as possible in the power system, taking into account the trade off between economic benefits and its capital costs.

The first phase of the energy storage system design procedure consists of the evaluation of the economic benefit of the lower thermal power plants generation that results from the operation of several power and energy capacity storage combinations. During the second phase, the capital costs of the several power and energy capacity of the storage systems are computed and the best solutions are identified.

In the case study presented for the Portuguese system it is showed that the implementation of the energy storage equipment in power systems with high penetration of renewable power sources, improves the power demand and generation balance and reduces the need for renewable generation curtailment.

Some power systems with large amount of hydro installed capacity, such as the Portuguese system, comprise reversible hydro power plants with energy storage capacity, usually used for the energy management improvement. Therefore, two opposite scenarios were considered: the first scenario is related to the pumping hydro system operation accordingly to the historic data; in the second scenario it was assumed that all of the pumping hydro installed capacity was available for helping the integration of the renewable power generation. As far the energy storage systems implementation is concerned, those scenarios allowed the identification of their maximum and minimum capacity requirements.

The availability of the installed pumping hydro systems, to cooperate in the integration of the renewable generation appears as a very positive solution for the power unbalance mitigation, especially when considering the costs of completely new energy storage systems implementation.

The energy storage system design process needs then to consider the physical constraints of power grid. Therefore, in order to validate the results from that process, namely the power flows imposed by the unit commitment problem outputs, a power system simulator was used (PSS/E - Siemens) for the simulation of the Portuguese transmission network model.

All the solutions were validated using the centralized energy storage concept. The solution that does not consider the pumping hydro availability had been validated also with the distributed energy storage at demand and the distributed energy storage at generation concepts. Regarding to the power grid losses, in this specific case study, the three different energy storage locations presented very similar results.

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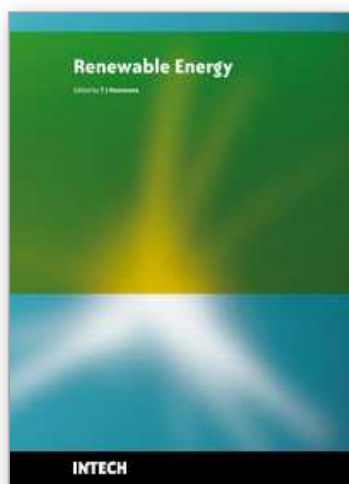
Renewable Energy

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Renewable Energy is energy generated from natural resources-such as sunlight, wind, rain, tides and geothermal heat-which are naturally replenished. In 2008, about 18% of global final energy consumption came from renewables, with 13% coming from traditional biomass, such as wood burning. Hydroelectricity was the next largest renewable source, providing 3% (15% of global electricity generation), followed by solar hot water/heating, which contributed with 1.3%. Modern technologies, such as geothermal energy, wind power, solar power, and ocean energy together provided some 0.8% of final energy consumption. The book provides a forum for dissemination and exchange of up-to-date scientific information on theoretical, generic and applied areas of knowledge. The topics deal with new devices and circuits for energy systems, photovoltaic and solar thermal, wind energy systems, tidal and wave energy, fuel cell systems, bio energy and geo-energy, sustainable energy resources and systems, energy storage systems, energy market management and economics, off-grid isolated energy systems, energy in transportation systems, energy resources for portable electronics, intelligent energy power transmission, distribution and inter-connectors, energy efficient utilization, environmental issues, energy harvesting, nanotechnology in energy, policy issues on renewable energy, building design, power electronics in energy conversion, new materials for energy resources, and RF and magnetic field energy devices.

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